CHAPTER 3

FINITE ELEMENT STUDY OF PORTLAND CEMENT CONCRETE PAVEMENTS WITH UTILITY CUTS

Introduction

A utility cut creates a discontinuity in the continuous medium of a Portland Cement Concrete (PCC) pavement causing stress concentrations and increased tensile stresses. Compounding this, the excavation often weakens the soil surrounding the cut, and the adjacent pavement often lacks proper support.

Currently, there are no mechanistic models for the analysis of PCC pavements with utility cuts. The only available mechanistic pavement models are those for highway pavements which are not applicable to analyze the effects of localized discontinuities, such as cuts. With the abundance of cuts made each year throughout the country, there is need to systematically analyze their effects on PCC pavements. This chapter presents the development and use of a mechanistic model created to simulate the behavior of PCC pavements with utility cuts. This tool is then used to investigate the deflections and tensile stresses in PCC pavements with cuts at different locations in the slabs and supported with variable subgrade stiffness.

Research Methodology

The utility cut problem may be idealized into a slab on grade problem with a discontinuity introduced as a result of the cut, where the slab may be modeled by Finite Elements (FE) and the subgrade by idealized springs. A Finite Element (FE) model, however, is only a mathematical model and it will simulate reality only if all the critical parameters governing the problem are incorporated. Once a model is created, it has to be validated with either accepted mathematical solutions, or with established software solutions. Alternately, field tests and measurements (deflections and stresses) may be used for validation. This process of calibrating the FE model solutions with computed or measured values is known as "system identification". This is an iterative procedure which involves modifying the initially assumed model so that, when loaded, its deflections or stresses compare well with those from theory or field measurements.

The Abaqus software was chosen to model the slab on grade problem with utility cuts, and to solve for strains, stresses and deflections due to selected loadings. One of the advantages of using Abaqus is its rich element library. The specific Abaqus model chosen for the analysis of PCC pavements with cuts consists of four-noded shell elements which are supported on idealized springs. This represents the FOUNDATION option in Abaqus, which provides stiffness per unit area in the direction perpendicular to the plane of the slab.

The analytical validation of the proposed FE software model was first undertaken by comparing the FE solution of a simple uncut PCC slab on a homogeneous subgrade with those from the classical Westergaard theory and from the well known ILLISLAB software. These comparisons are described in subsequent sections.

Any FE study requires inputs from the field. This involves an experimental investigation to measure field parameters and results to feed the System Identification process, that is, to calibrate the model. The investigation was divided into two phases. Initially the effect of discontinuity in the concrete slab was studied without disturbing the subgrade soil. The test sections were selected and a rectangular discontinuity of a size of a typical cut (4 feet by 5 feet) was introduced in the center of each slab These test sections are referred to as "mock cuts" in the following discussions Deflection studies were carried out using the Falling Weight Deflectometer (FWD). These gave an understanding of the weakening caused by the discontinuity in the slabs and also indicated whether the FE model was successfully simulating the true mechanism of pavement behavior Next. field deflection studies were carried out on an actual in-service cut with potentially weakened subgrade soil. These were conducted using the Dynaflect equipment.

The System Identification process was carried out by comparing the measured and predicted values first for the mock cuts and then for the in-service cut. At this stage, the final calibrated model was available which closely simulated the field conditions. This mechanistic model was then used to conduct a parameter study to find the critical location of cuts, and the effect of subgrade stiffness on the pavement slab.

Model Validation Using Analytical Solutions

Model validation can be accomplished by comparing the FE solution with a standard analytical solution. Alternatively, the FE solution may be compared to one obtained from the use of an accepted software which relies on a different analytical basis.

To test the suitability of Abaqus for solving slab on grade problems, a representative model slab of dimensions 12 feet by 15 feet by 7 inches thick was selected, that rested on a soil with a subgrade reaction of k = 200 pounds per cubic inch. Symmetry was used to allow the analysis of one-quarter of the slab only, Figure 3.1. A 9,000 pound wheel load was applied at the center of the slab and the deflections were computed. Figure 3.2 shows the mesh pattern used and the deflected profile of the slab. Figure 3.3 gives the distribution of the von Mises stresses in the slab.

Comparison of the Abaqus Model Results with Westergard's Solution. The midslab deflection of the 12 foot by 15 foot slab described above, using the Abaqus model solution, was found to be 0.0078 inches. This was compared to the midslab deflection of a slab on elastic foundation according to the classical solution by Westergaard, which gave a deflection of 0.0072 inches. They show good agreement.

Comparison of the Abaqus Model Results with the ILLISLAB Solution. ILLISLAB is a custom made software for slabs resting on subgrade. It is a thoroughly tested software and it is known to have experimental comparisons for a variety of pavement problems. In the ILLISLAB Model of the 12 foot by 15 foot slab, one quarter of the slab was simulated with a mesh pattern identical to that of the Abaqus Model. ILLISLAB Version IST=6 was used which simulates a foundation using a consistent spring foundation (similar to consistent mass matrix in dynamics). Figure 3.4 shows the deflections along the line of symmetry AB for both Abaqus and ILLISLAB solutions. They show very good agreement.

Model Calibration Using Experimental Data

It has been shown above that the Abaqus software will properly model the deflections in PCC slabs without utility cuts. An experimental program was conducted to ascertain that the model also can simulate slabs with utility cuts. This was accomplished by measuring the deflections of several PCC pavement sections with cuts and comparing these deflections with those obtained from the Abaqus solutions.

Two dynamic, non-destructive testing devices were used to produce dynamic field deflections; the Falling Weight Deflectometer (FWD) and the Dynaflect. Both of these devices measure the deflection profiles, or deflection bowls, by a set of Geophones. For System Identification, a measured deflection bowl of the pavement can be compared to the deflection bowl from the Abaqus solution. Also, the measured deflection bowl, and pavement layer thicknesses, can be used to calculate the pavement layer properties by an elastic theory. This is called the Backcalculation process.

Use of Test Sections with Mock Cuts: Three test sections were selected around the City of Cincinnati representing different soil and traffic conditions. Typically, the cuts were 4 feet by 5 feet in size, cut by sawing, and positioned in the middle of PCC slabs of approximately 12 feet by 15 feet. The cuts were not excavated, so the uniformity of the subgrade was not disturbed. By double cutting at the edges and removing the resulting one inch wide sliver of perimeter concrete, it was assured that there was no shear transfer between the concrete pad inside the cut and the surrounding pavement slab.

Extensive deflection studies were conducted on these test sections using the Falling Weight Deflectometer. The deflection profiles were obtained to calibrate the Abaqus finite element model, and to backcalculate the pavement layers' properties. At each site, two adjacent slabs were tested, one containing the cut and the one without the cut, also known as the control section. The control section was typically used to backcalculate the pavement material properties, assuming no variation in properties between the two adjacent slabs. The configuration selected was the same for all test sites. However, the dimensions of the pavement slabs varied slightly for the different sites. Figure 3.5 shows the plan view of the test sections and the different loading positions selected to obtain the deflection profiles. Three loading positions, marked 1, 2, and 3, were used in the control section to improve the reliability of the deflection bowls. The deflection profiles for the test sites are shown in Figures 3.6.a through 3.6.c. For all test sites the control section deflections (loading positions 1, 2 and 3) were found to be quite close. This consistency in the results built confidence for using the data for backcalculation purposes, and for model calibration. The load placed along the edge of the cut (loading condition 4) produced an expected cantilever deflection profile indicative of a loss in continuity at the edge of the cut. The deflection profile for loading condition 5 shows an expected smooth continuous curve at the maximum deflection point.

The Backcalculation Results The aforementioned backcalculation process resulted in the elastic moduli of the slabs, and their average value was found to be approximately 6.5 x 10^6 psi.

System Identification (Calibration) for Mock Cuts: A finite element model was created for each of the test sections in the Abaqus software. This modeling involved geometry modeling, choice of elements and their sizes, boundary conditions, loading conditions, and material properties.

Again, the plan view for the test sections is shown in Figure 3.5. These geometries and the pavement slabs were modeled by an assembly of four-noded shell elements. The soil was modeled as a spring foundation. The typical mesh configuration used is shown in Figure 3.7.

Regarding boundary conditions, the discontinuity at the joints between two slabs had to be idealized in the FE model. From FWD measurements it was found that the typical load transfer at the joints was better than 90%. Therefore, in the Abaqus model, perfect shear transfer, but no moment transfer, was assumed at the joints.

The loading positions selected for the field deflection study are shown in Figure 3.5. In the model the loading was simulated by placing a concentrated load equal in magnitude to the one applied in the field, and at a position that corresponded to the true field position.

In the System Identification process, the Abaqus FE solutions were executed iteratively to match the deflection profiles measured in the field by the FWD. In this process, it was decided to use the backcalculated values of E of concrete and "fine-tune" the k of subgrade soil. The appropriate combination was found to be E(conc) = 6.5×10^6 psi and k(soil) = 228 pci (average of 3 values for the mock cuts). Calibration results, shown in Figures 3.8 through 3.10, indicate that the deflection profiles match well, being within acceptable levels of accuracy.

System Identification (Calibration) for a Real-Life Cut: To enlarge the sample size of System Identification and to gain further confidence in the appropriateness of the values of E(conc) and k(soil) from the mock cut system identification process, an additional cut was tested and analyzed. This time an actual utility cut was modeled by the Abaqus FE software and calibrated by using deflections produced by the Dynaflect deflection device. The measurements were made on an utility cut in the PCC pavement of Calvert Street, Cincinnati.

Figure 3.11 shows the layout of the test site and the various load positions used in obtaining the deflection profiles. The pavement slab was modeled again using shell elements, Figure 3.12, and the soil subgrade was modeled by spring foundations, but having different k values for three distinct regions, such as k_1 for the backfill, k_2 for the soil subgrade in the immediate vicinity of the cut (within 3 feet from the edge of the cut) to simulate the potentially weakened subgrade in this region, and k_2 for the rest of the subgrade, as shown in Figure 3.13. For these finite element analyses, perfect shear and zero moment transfer was assumed at the cut to pavement boundary. The loading points and the load magnitude for the FE analyses are the same as were used in the field measurement of the deflection bowls by the Dynaflect device, Figure 3.11.

The Abaqus FE analysis was run for various trial material properties trying to match the deflection profiles measured in the field. The final results for the Calvert Street cut are shown in Figure 3.14. The results show good comparison. All three deflection profiles (for center point, for the point one foot away from the edge of cut, and at the control section) converged for the values of E(conc) = 6.5×10^6 psi and $k_3 = 320$ pci, with $k_1 = 0.95\ k_3$ and $k_2 = 0.875\ k_3$.

A Preliminary Parameter Study

Having satisfactorily converged the solution from the Abaqus FE model with the measured field results, for both the mock cuts and the actual utility cut, the model may now be used to conduct parameter studies. In these, the use of the average values of E(conc) = 6.5×10^6 psi and k = 250 pci is recommended for PCC pavements and clay subgrades in the City of Cincinnati.

The model developed and described in the preceding sections can be used to study how maximum stresses in PCC pavements are affected by factors such as cut location within the pavement slab and the stiffness of the cut backfill and the surrounding subgrade. This preliminary parameter study involved moving a cut with typical dimensions of 4 feet by 5 feet into various positions in a PCC pavement that was 15 feet long by 12 feet wide and 8 inches thick, then analyzing to determine the maximum stresses corresponding to each position.

Conditions assumed were:

(1) A pavement (modeled by four-noded shell finite elements) with elastic modulus of 6.5 x 10^6 psi and Poisson's ratio of 0.15; pavement modulus of rupture of 770 psi (11.08 x 10^4 psf).

(2) Subgrade idealized as a "consistent spring foundation" with a modulus of subgrade reaction of 250 pci.

(3) Perfect shear transfer and no moment transfer along the boundary between the utility cut and the surrounding pavement slab.

(4) Perfect shear transfer and no moment transfer at the joints between the PCC slabs.

(5) A wheel load of 9000 pounds applied at selected locations around the edge of the cut.

The first set of analyses was started by placing the cut in the center of the pavement, Figure 3.15. The cut was next moved to the edge at the interior joint of the pavement, Figure 3.16, and then to an interior corner of the pavement, Figure 3.17. Load locations also are shown. The FE analysis yielded the maximum stresses in the pavement, given as the von Mises stresses. These, in turn, can be directly compared with the modulus of rupture

(MR = 770 psi = 11.08 x 10^4 psf) of the concrete to check if cracking may occur in the concrete. The maximum von Mises stresses for the three different cut locations are tabulated in the upper three rows of Table 3.1. Of the three cut positions, the analysis showed that cutting at an interior corner was the most critical, resulting in a maximum von Mises stress of 2.78 x 10^4 psf.

The three cuts considered so far had adjacent pavements to help support the wheel loads through shear transfer at the joints. However, the stresses are likely to intensify when the utility cut is placed at the curb where there is no edge support. This case is shown in Figure 3.18. The von Mises stresses for the different load positions are again shown in Table 3.1. As seen, the intensity of stresses is higher than for the previously considered cut locations. In fact, the stress in the concrete at load location 3, 5.01 x 10^4 psf, came very close to one-half of the modulus of rupture, 5.54 x 10^4 psf, which in this study will be considered the maximum allowable stress. Exceeding this level of stress may cause fatigue cracking of the slab at some future time (after a large number of load repetitions).

A further parameter study was conducted to analyze the effect of reductions in concrete strength and subgrade stiffness. The assumed properties were: E(conc) = 4 x 10^6 psi, Poisson's ratio of 0.15, pavement modulus of rupture = 9.54 x 10^4 psf (662 psi), allowable von Mises stress = 4.77 x 10^4 psf, thickness of slab of 9 inches, and modulus of subgrade reaction = 200 pci. Assuming exactly the same four cut locations as in the preceding analysis, new analyses were conducted. Figures 3.19.a through 3.19.c show the variation in stresses for the center cut and for the three load positions. The summary of the resulting stresses are given in Table 3.2. As seen, the maximum stress in the pavement at the corner cut came close to the allowable, 4.04 x 10^4 psf versus 4.77 x 10^4 psf, and the maximum stress in the slab at the cut on the curb greatly exceeded the allowable stress, that is, 7.26 x 10^4 psf versus 4.77 x 10^4 psf.

Using the above weaker concrete, E(conc) = 4 x 10^6 psi, a further study was conducted to investigate the effect of variations in subgrade stiffness for the case when the cut was placed at the curb. The results are tabulated in Table 3.3. As seen, the modulus of subgrade reaction had appreciable effect on some stresses, but relatively little effect on the absolute maximum stress.

In summary, the preliminary parameter study shows that a utility cut placed near the curb results in the greatest von Mises stresses in the pavement. In fact, with weaker concrete (E = 4 x 10^6 psi), a truck wheel load will most likely break the concrete pad over the cut.

Further studies should be conducted to investigate the effect of cuts in thinner concrete slabs, such as a 7 inches thick slab. Also, the case where a cut is made near an interior joint should be checked, when only a narrow concrete strip between the joint and the cut is left and a truck wheel load is applied in the middle of this strip.

Table 3.1. Von Mises Stresses for Different Cut Locations and Load Positions
(E conc = 6.5×10^6 psi , k = 250 pci)

Cut Location	Load Position					
	1	2	3	4	5	6
Center cut	2.016	1.911	2.009	-	-	-
Edge cut at interior joint	2.001	1.822	2.065	2.578	-	-
Corner cut	2.768	1.874	1.493	2.033	2.783	1.913
Cut on Curb	1.882	3.20	5.006	3.406	2.73	2.020

Note: Stresses in 10^4 psf
Modulus of Rupture of Concrete = 11.08×10^4 psf (770 psi)

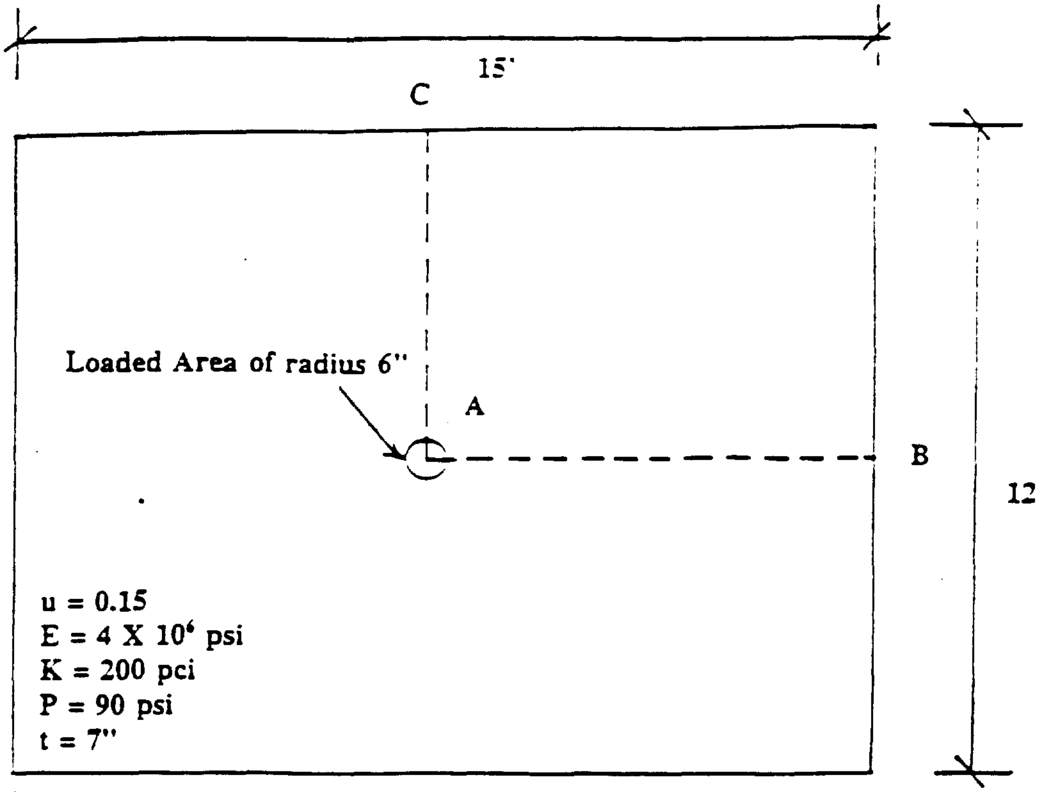
Table 3.2. Von Mises Stresses for Different Cut Locations and Load Positions
(E conc = 4.0×10^6 psi, k = 200 pci)

Cut Location	Load Position					
	1	2	3	4	5	6
Center cut	2.923	2.771	2.913	-	-	-
Edge cut at interior joint	2.90	2.64	2.99	3.74	-	-
Corner cut	4.013	2.71	2.164	2.94	4.035	2.77
Cut on Curb	2.73	4.65	7.26	4.94	3.96	2.93

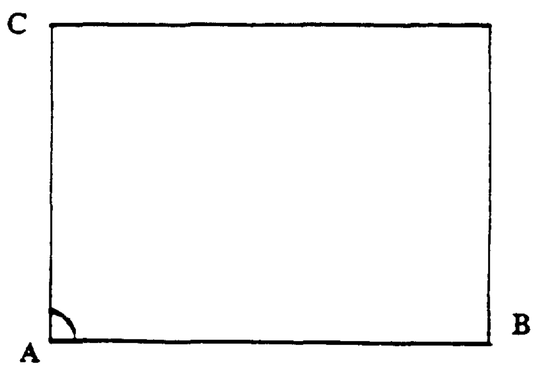
Note: Stresses in 10^4 psf
Modulus of Rupture of Concrete = 9.54×10^4 psf (662 psi)

Table 3.3. Sensitivity of Maximum Stress with k
for Cut at the Curb

Subgrade Modulus K (pci)	Maximum Stress for Load Condition # 1 (X 10^4 psf)	Maximum Stress for Load Condition # 2 (X 10^4 psf)	Maximum Stress for Load Condition # 3 (X 10^4 psf)
50	4.14	5.25	7.94
100	3.29	4.91	7.64
150	2.96	4.75	7.43
200	2.73	4.65	7.26
250	2.58	4.56	7.19



a) Plan View of Full Slab (not to scale)



b) Quarter Slab for Analysis

FIG. 3.1. Details of Model Slab for Testing the Abaqus Model

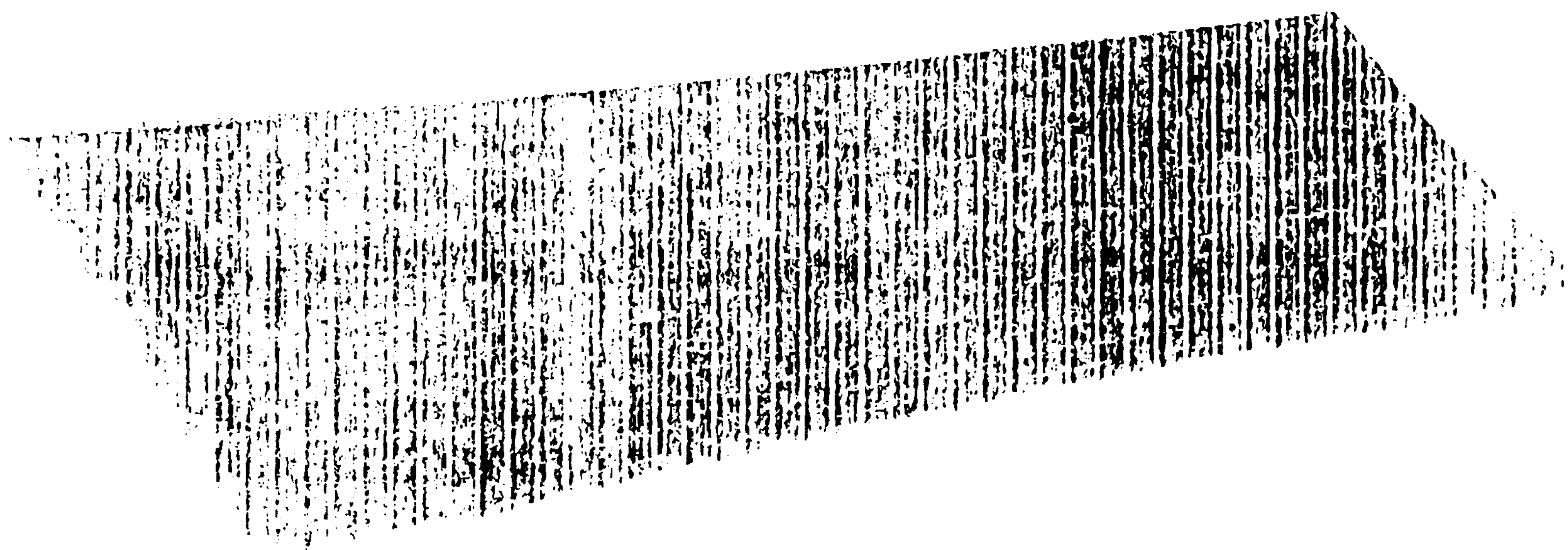


FIG. 3.2. Deflected Shape of the Model Slab

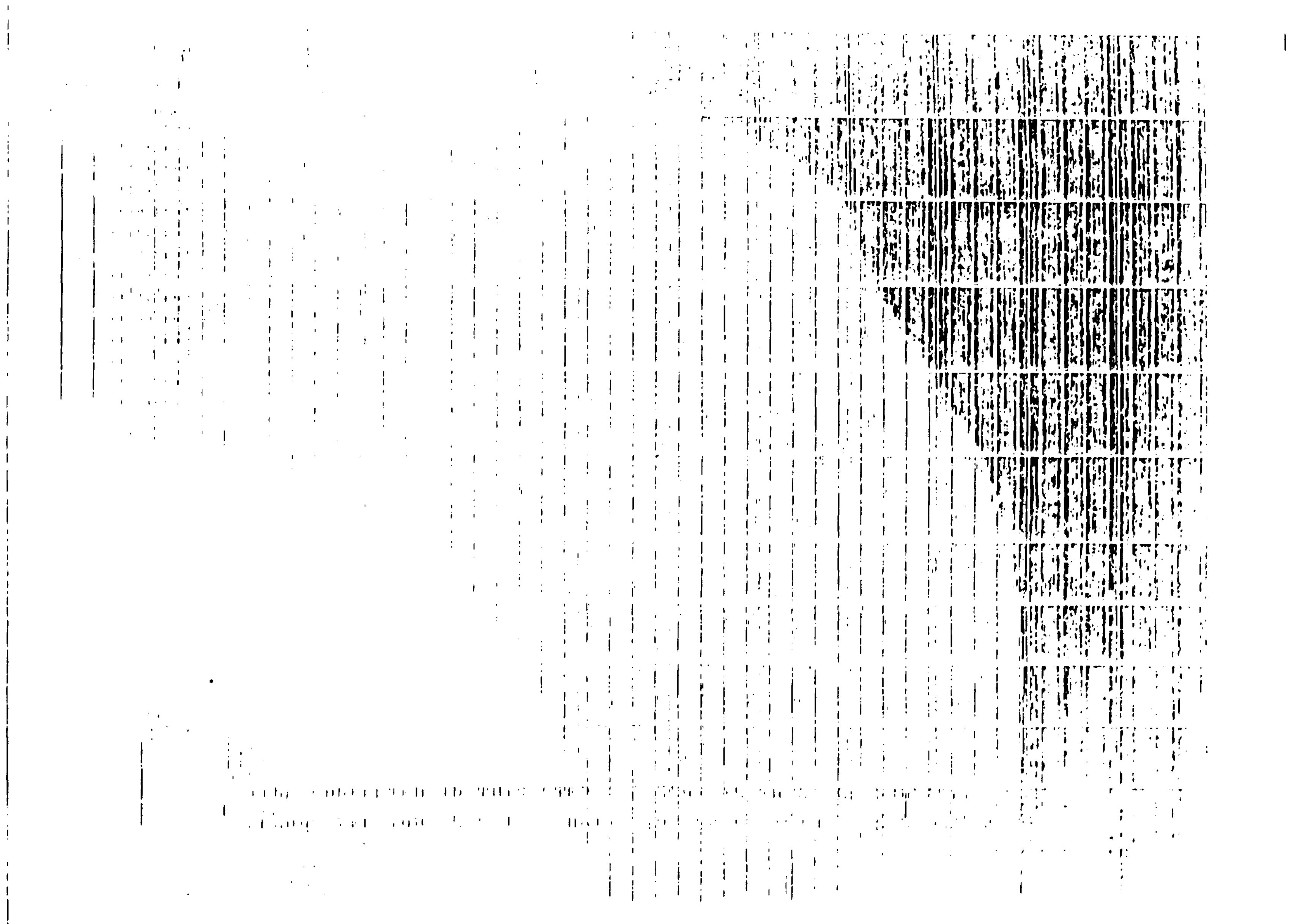


FIG. 3.3. Distribution of von Mises Stresses in the Model Slab

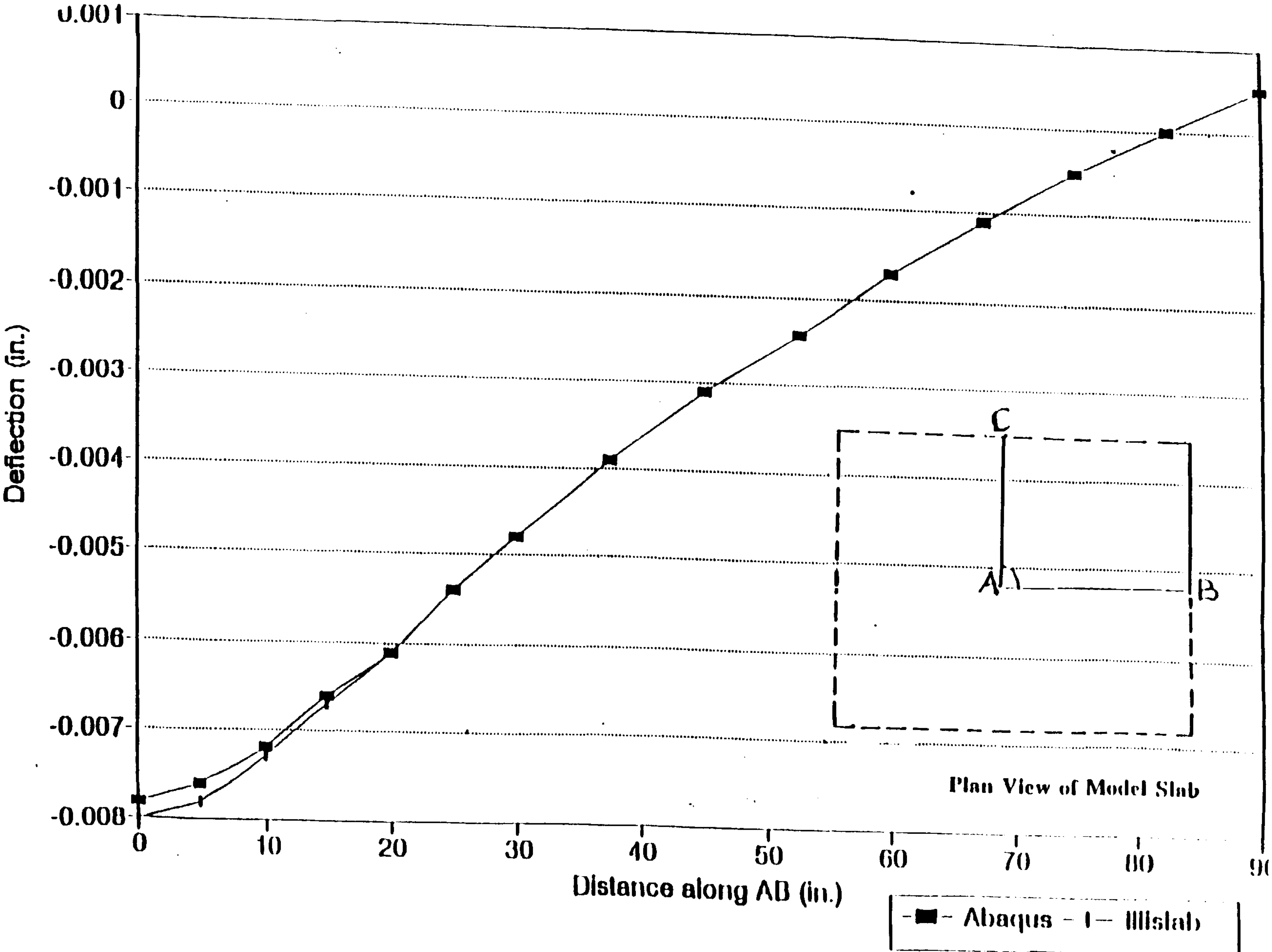
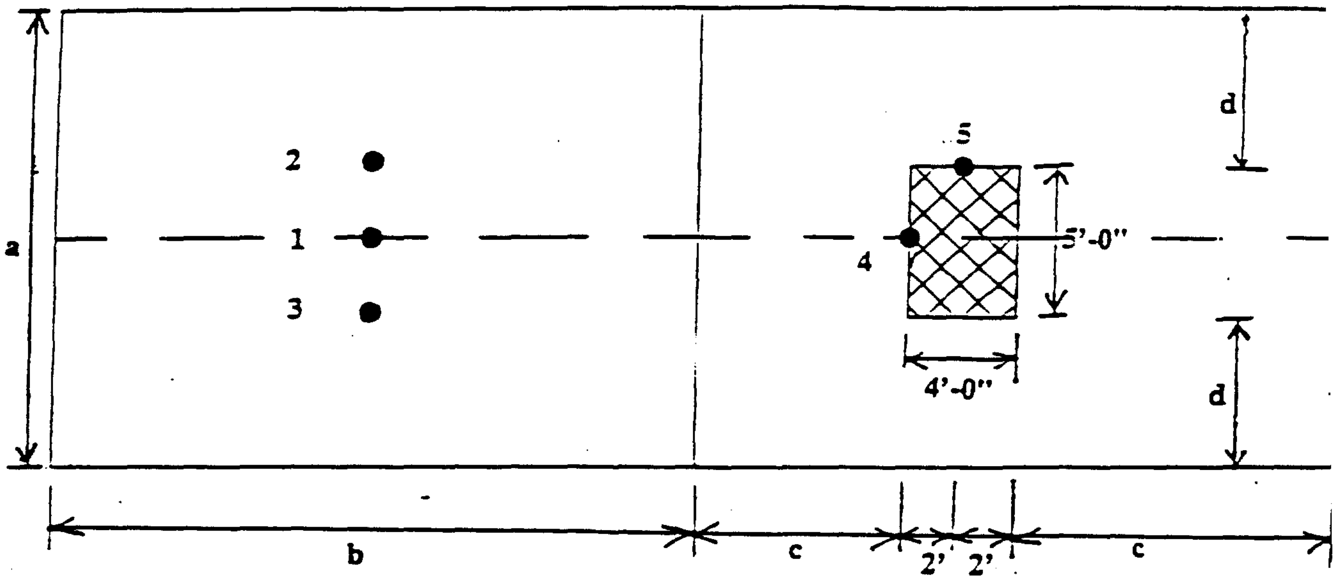


FIG. 3.4. Comparison of Abaqus vs. Illislab Deflections of Model Slab



NOTE : ● Designates Loading Position

For Calvert Street : a = 130" b = 184" c = 68" d = 35"

For Jefferson Ave. : a = 130" b = 176" c = 64" d = 35"

For Wasson Road : a = 120" b = 178" c = 65" d = 30"

FIG. 3.5. Plan View of Test Sections for Mock Cuts

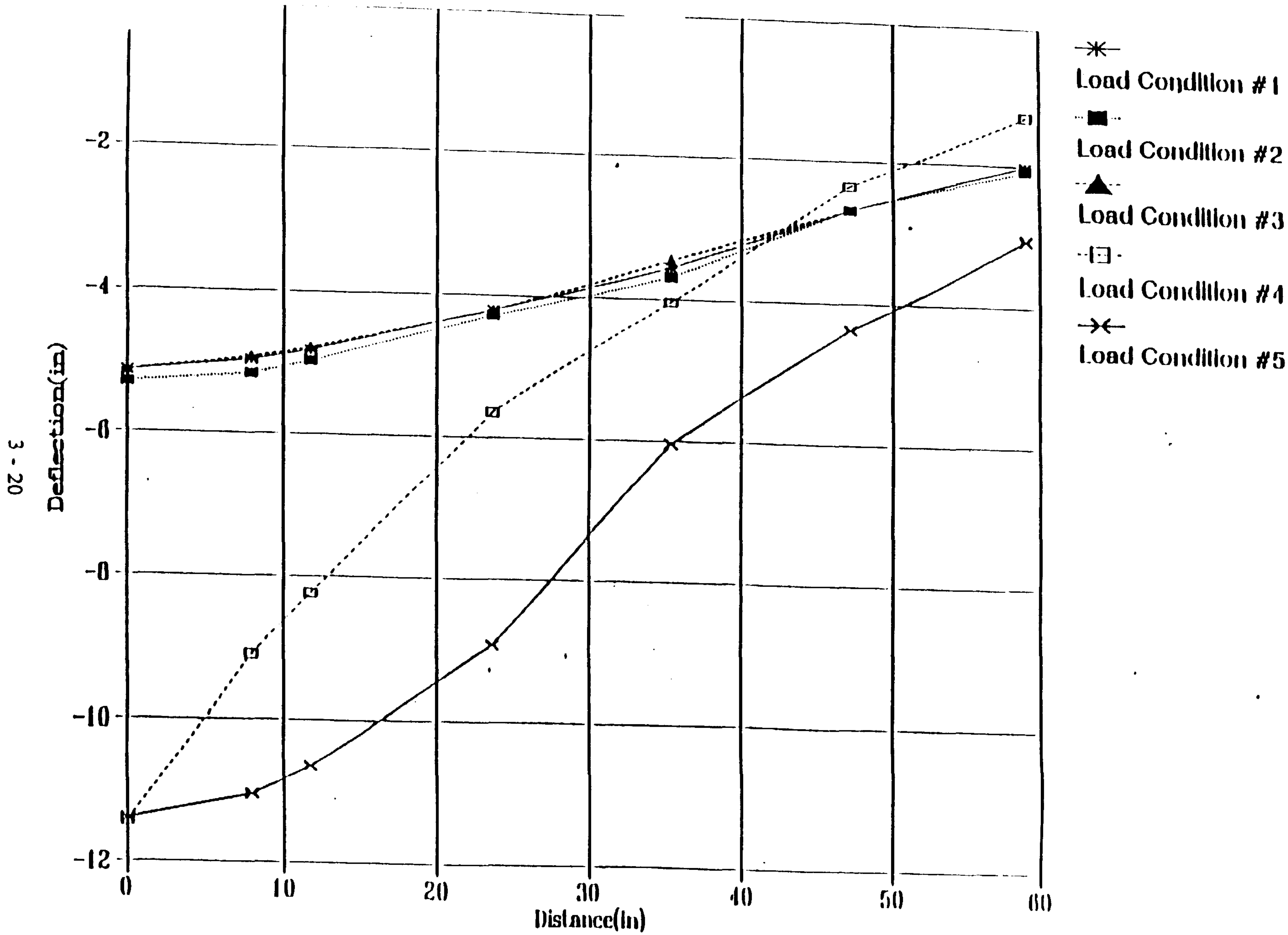


FIG. 3.6.a. FWD Deflection Profiles for Wasson Road

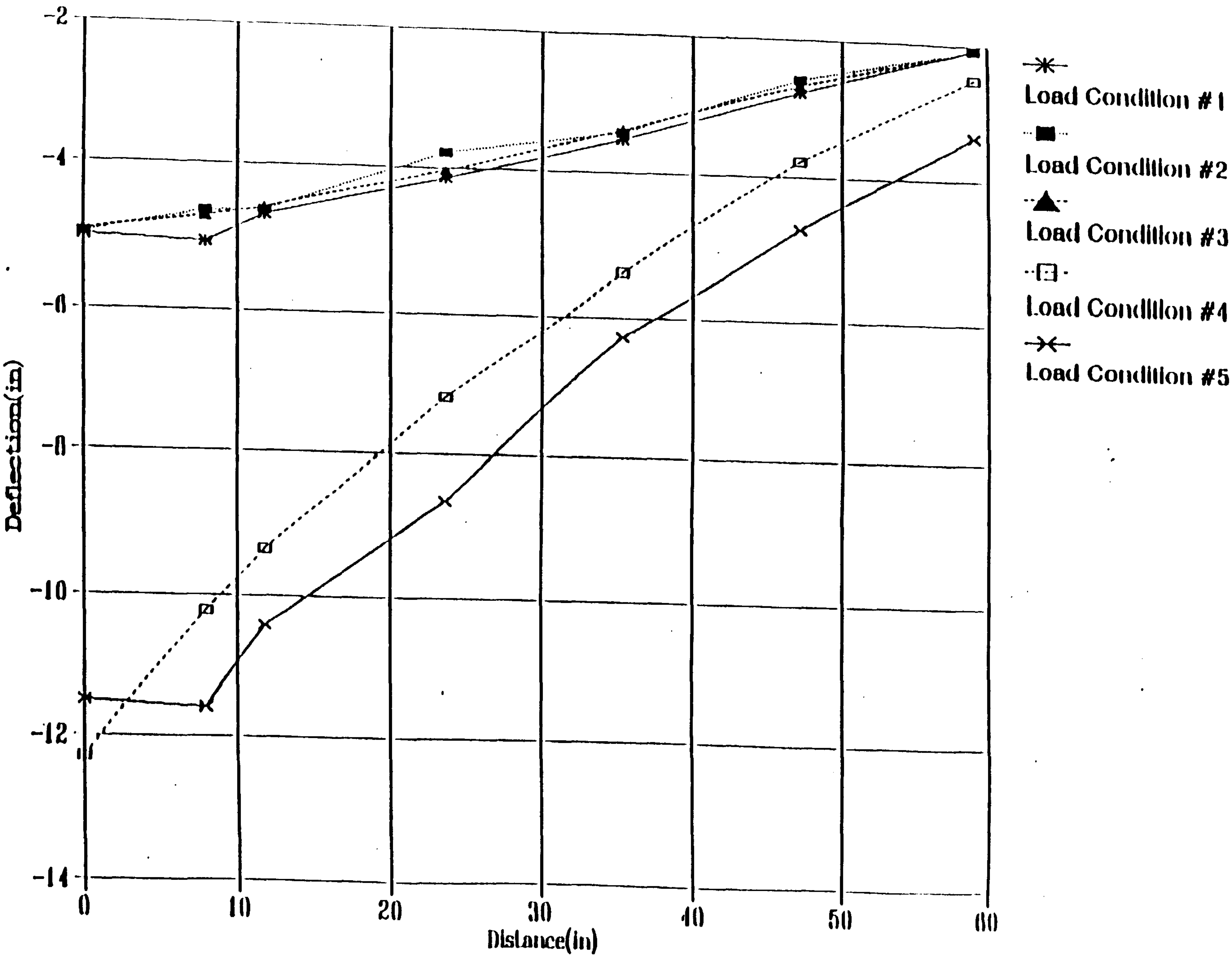


FIG. 3.6.b. FWD Deflection Profiles for

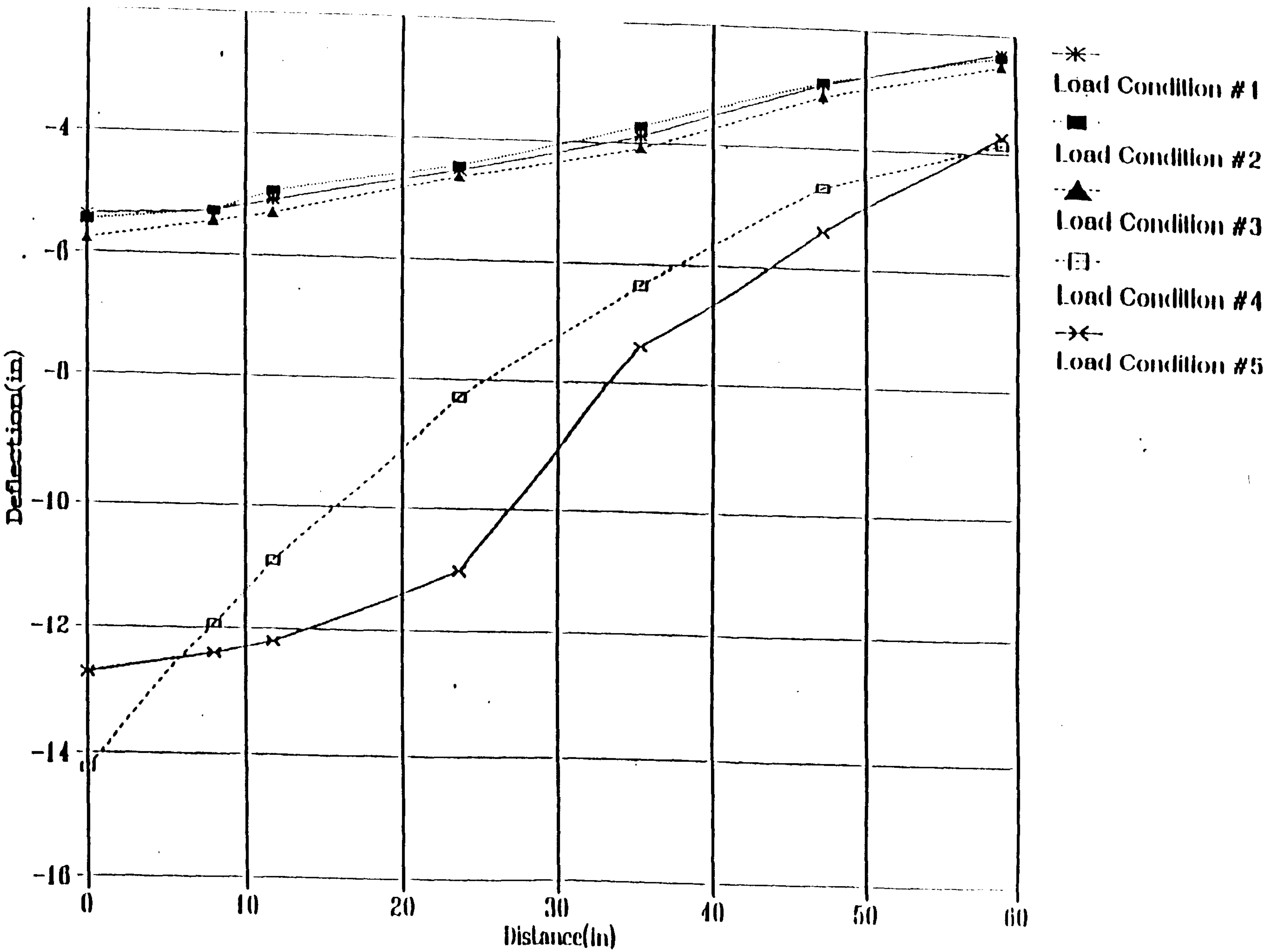


FIG. 3.6.c. FWD Deflection Profiles for Jefferson Avenue

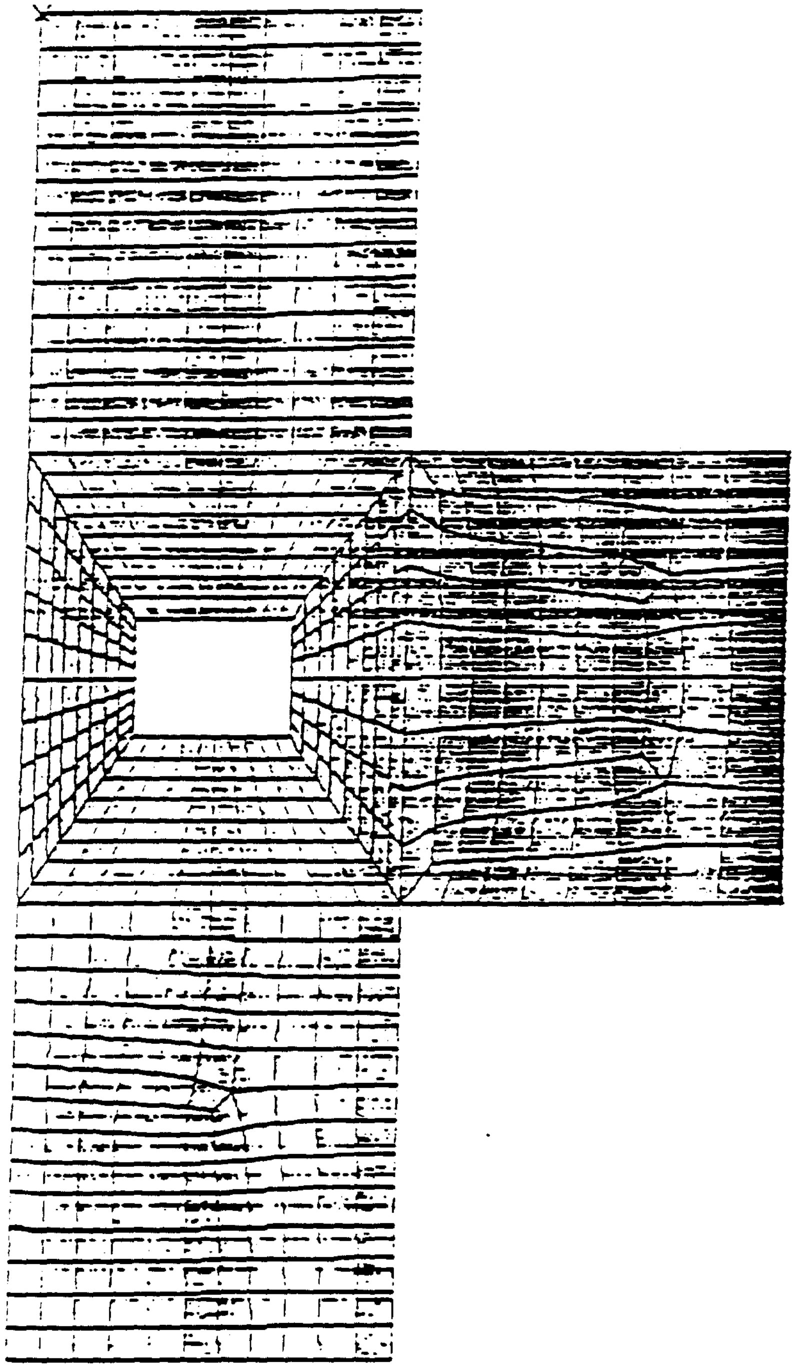


FIG. 3.7. Mesh Configuration for the Mock Cuts

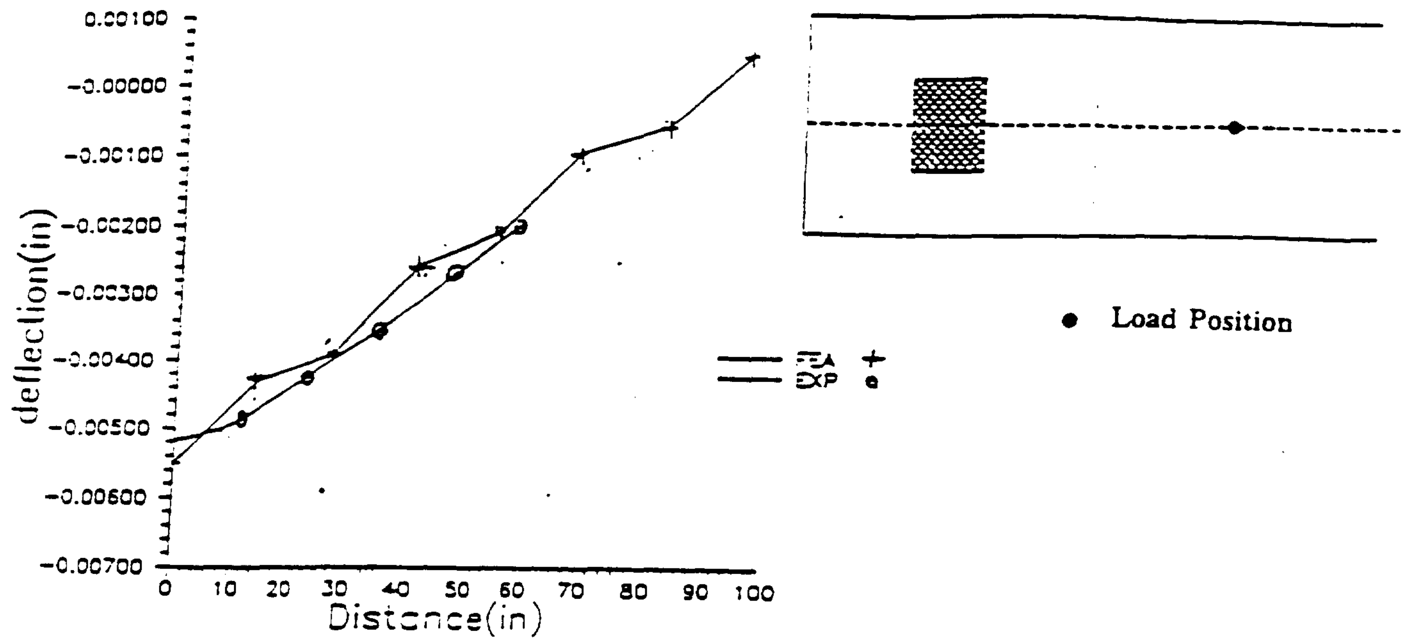


FIG. 3.8.a. Deflection Profiles for Wasson Road (Control Section)

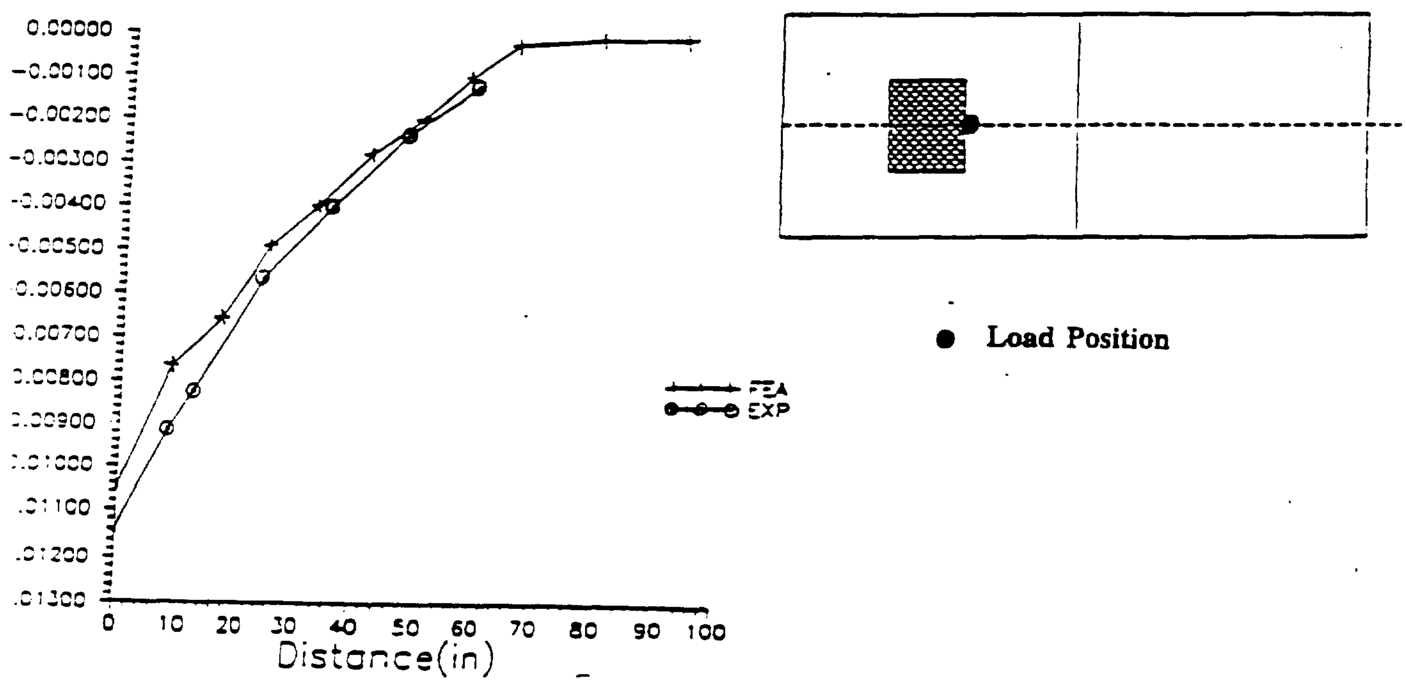


FIG. 3.8.b. Deflection Profiles for Wasson Road (at Cut)

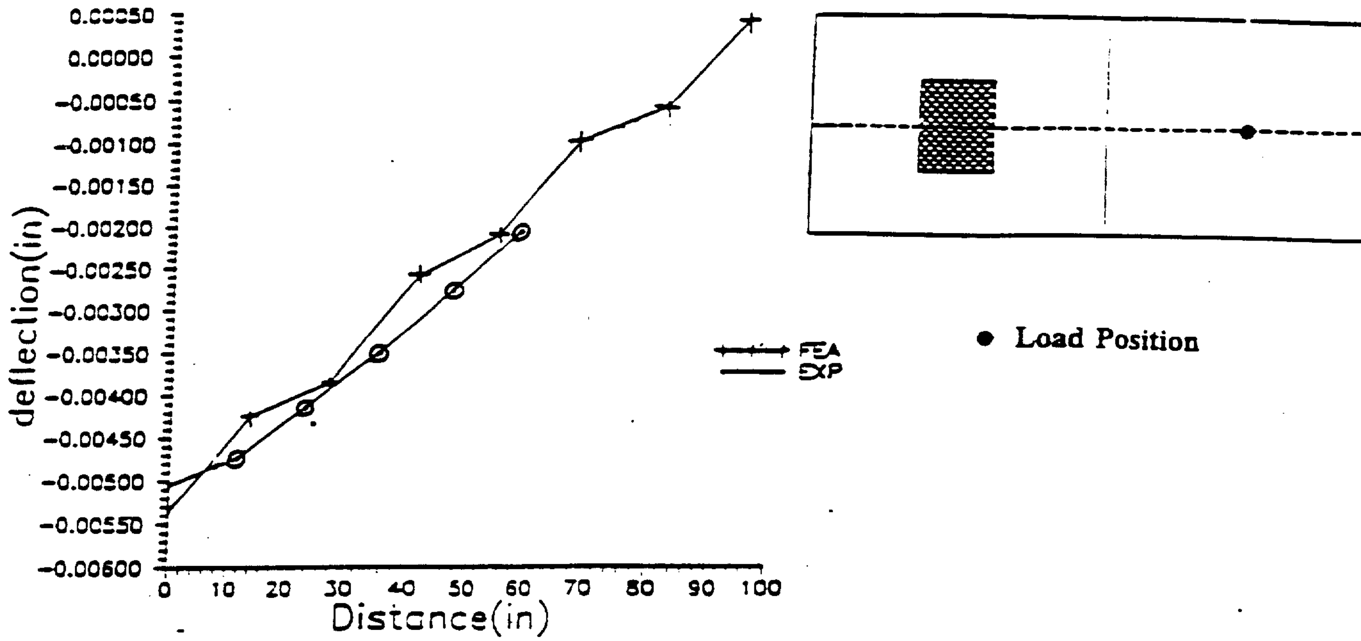


FIG. 3.9.a. Deflection Profiles for Calvert Street (Control Section)

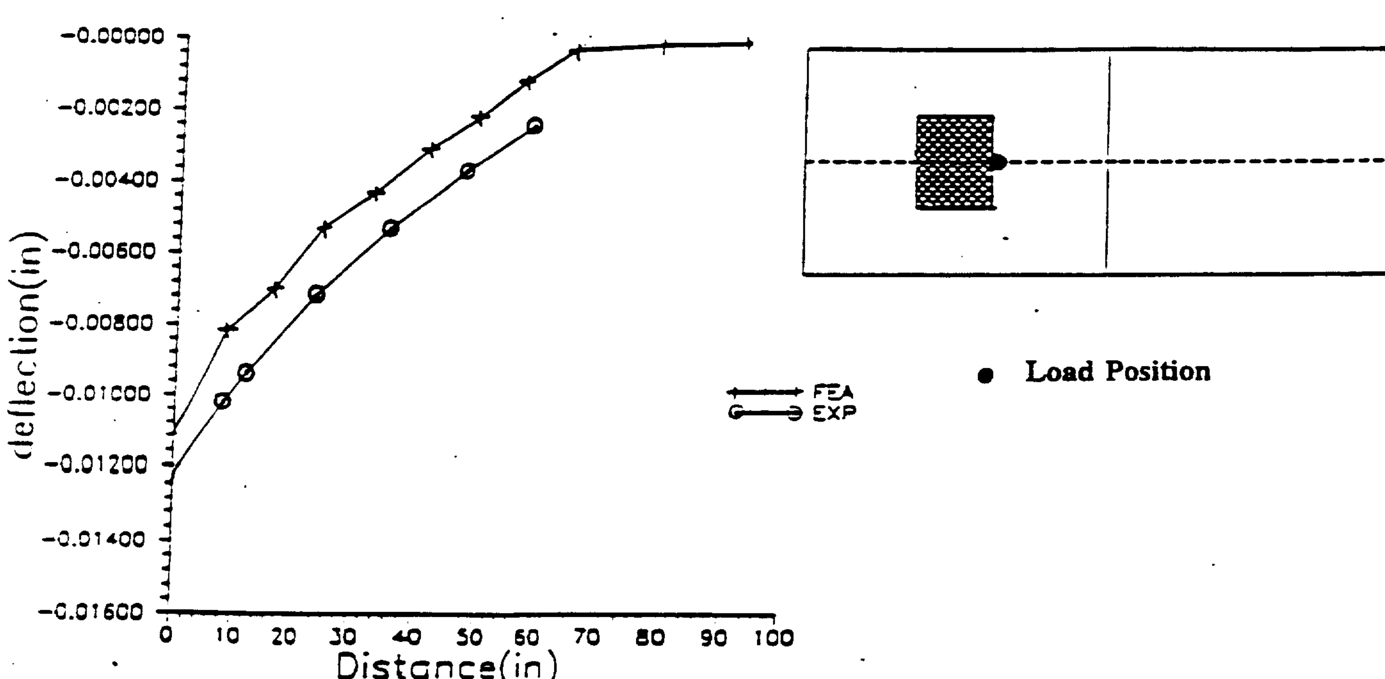


FIG. 3.9.b. Deflection Profiles for Calvert Street (at Cut)

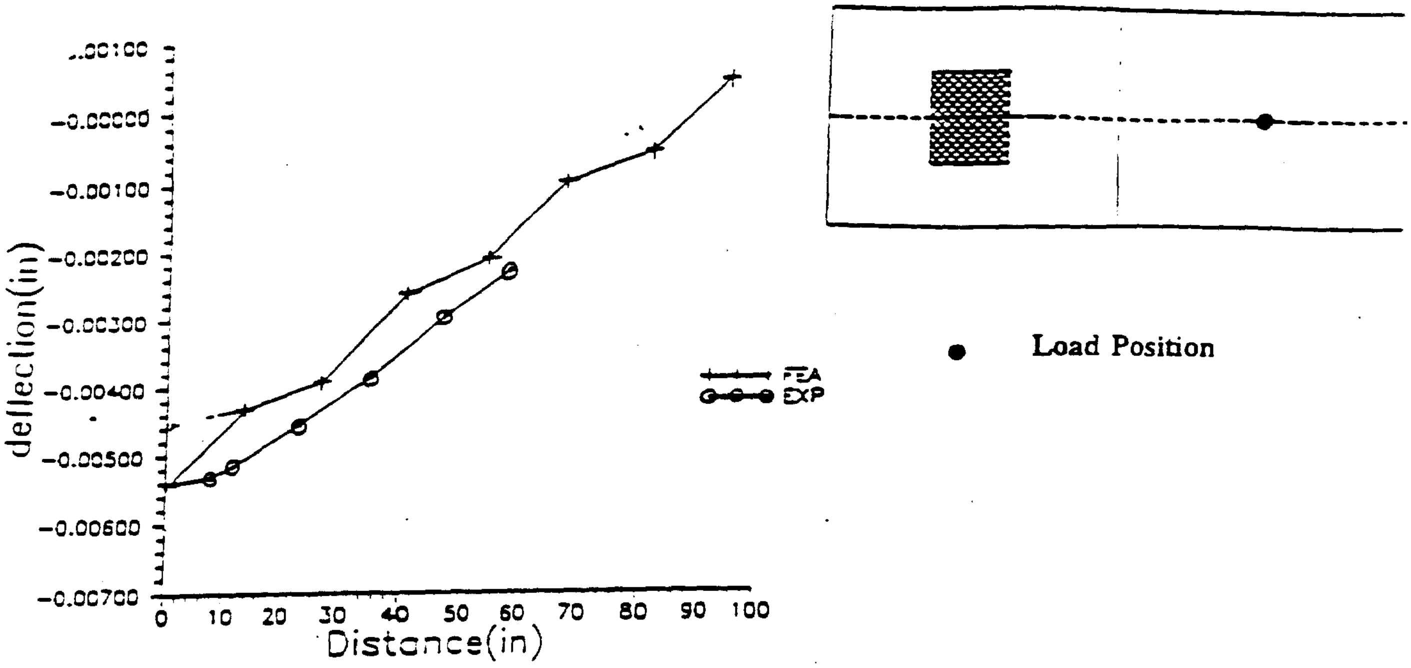


FIG. 3.10.a. Deflection Profiles for Jefferson Avenue (Control Section)

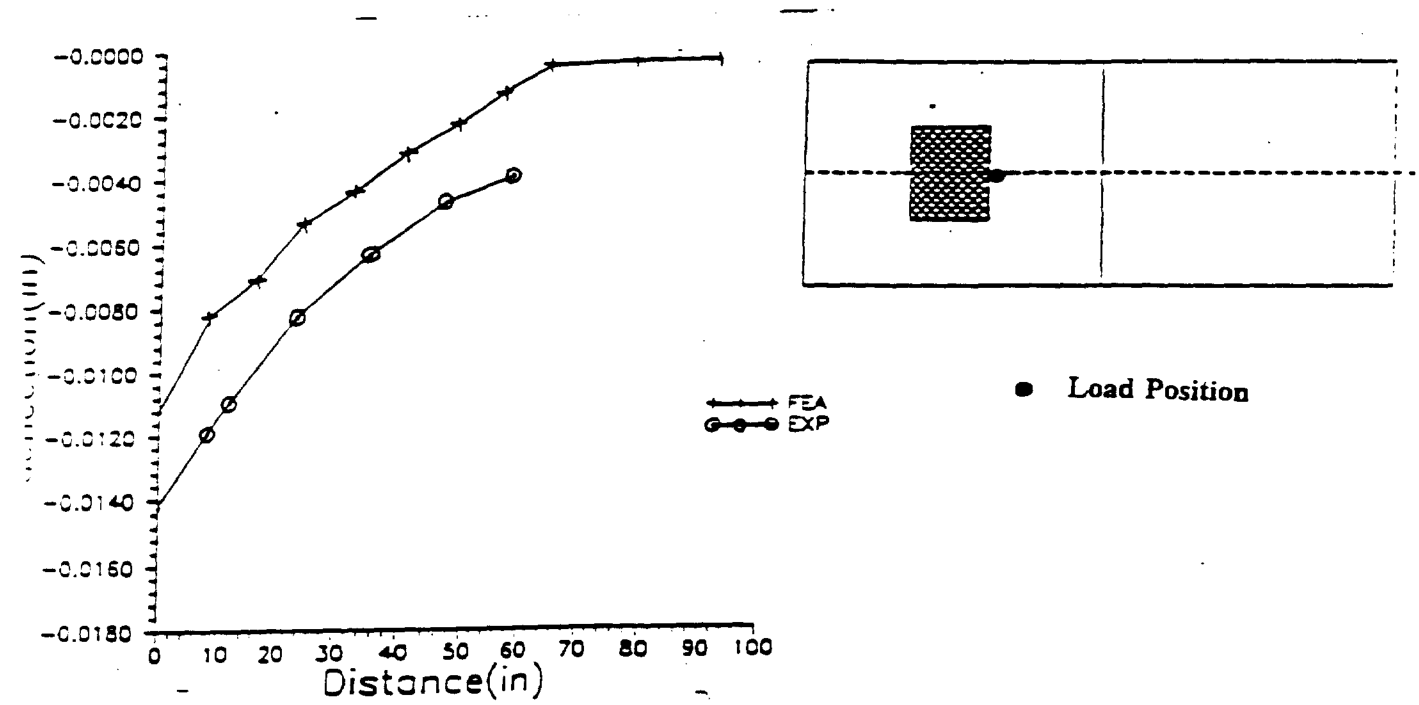


FIG. 3.10.b. Deflection Profiles for Jefferson Avenue (at Cut)

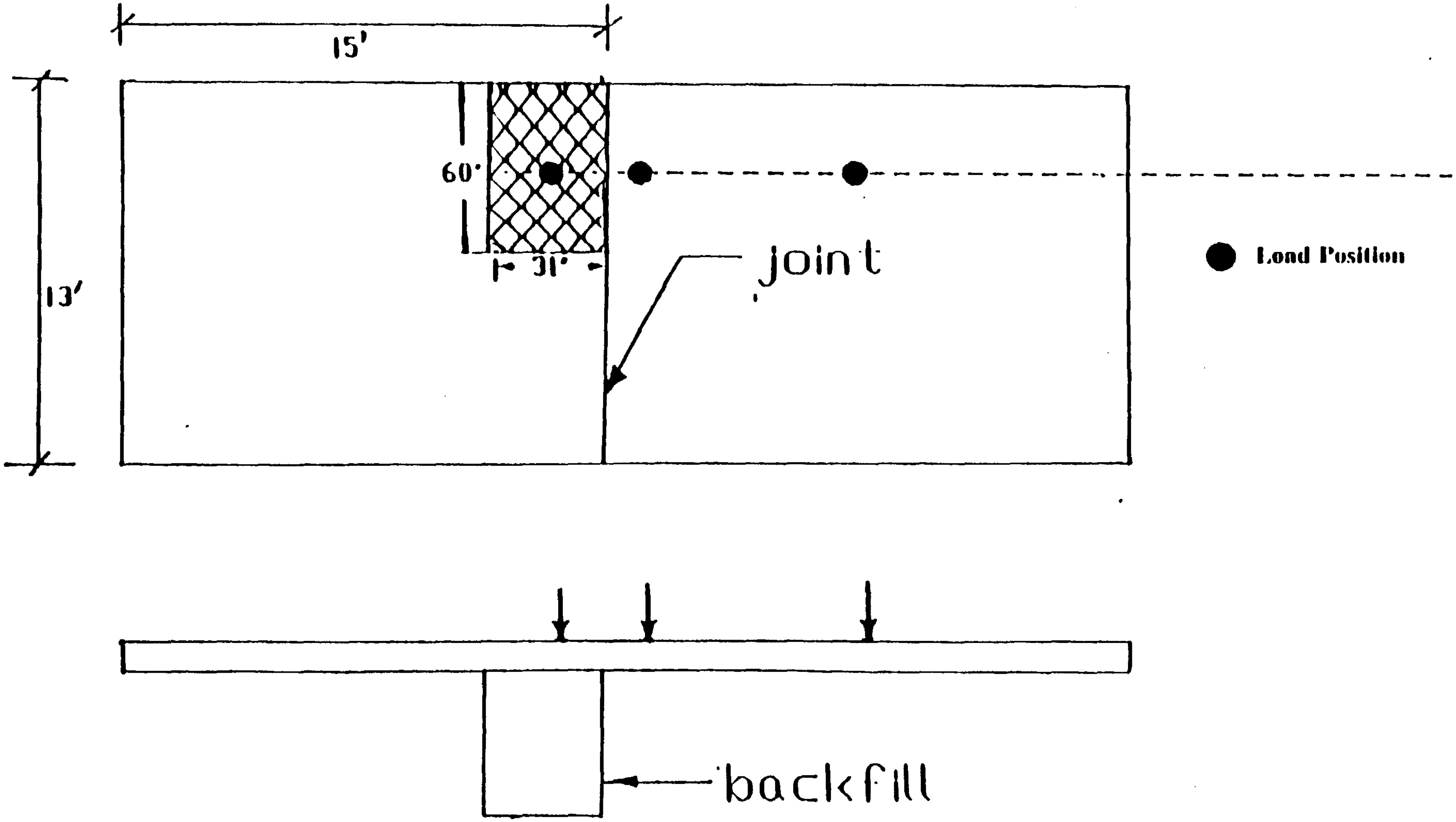


FIG. 3.11. Layout for Dynaflect Tests on Calvert Street

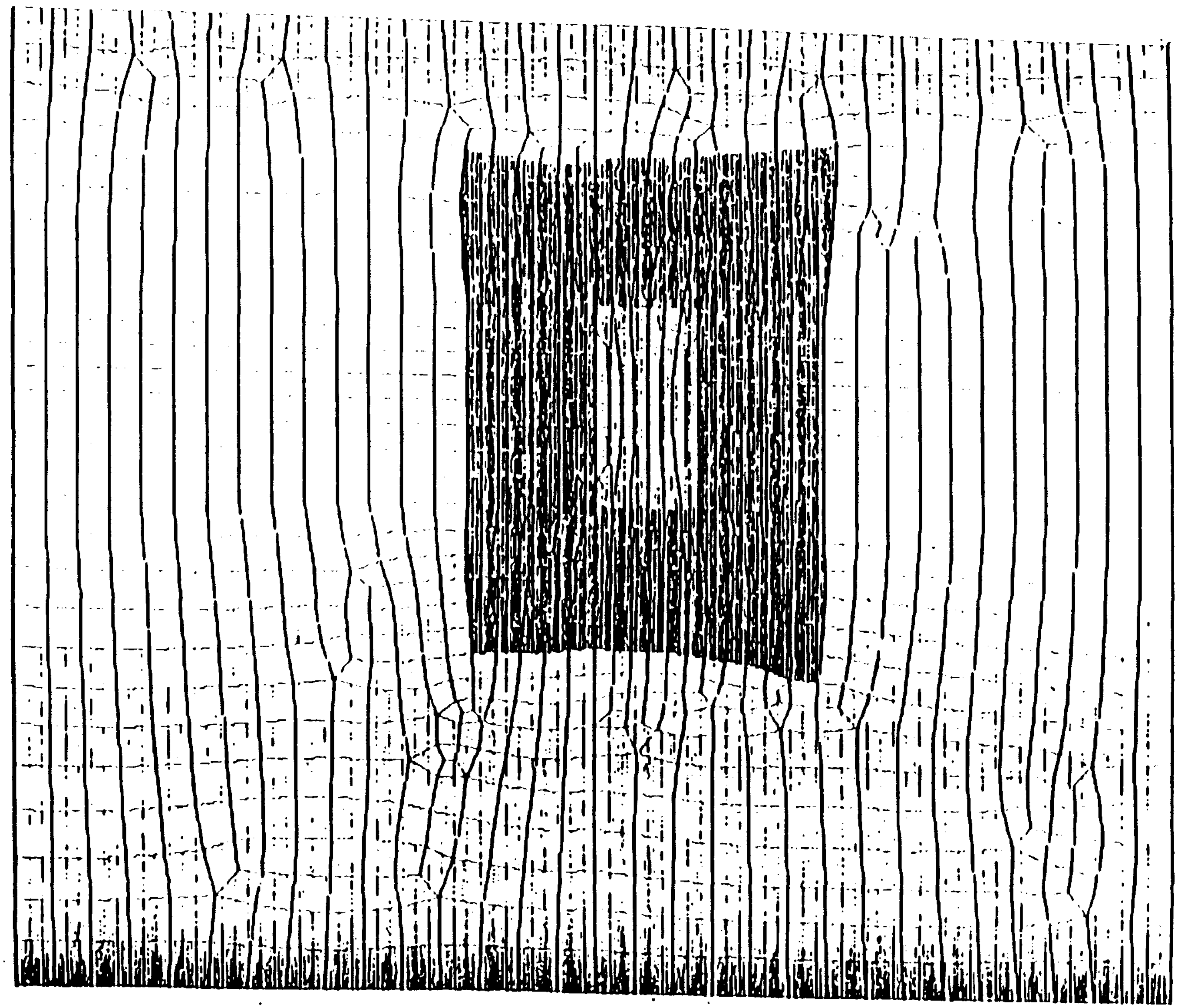


FIG. 3.12. Mesh Configuration for Dynaflect Test Modeling on Calvert Street

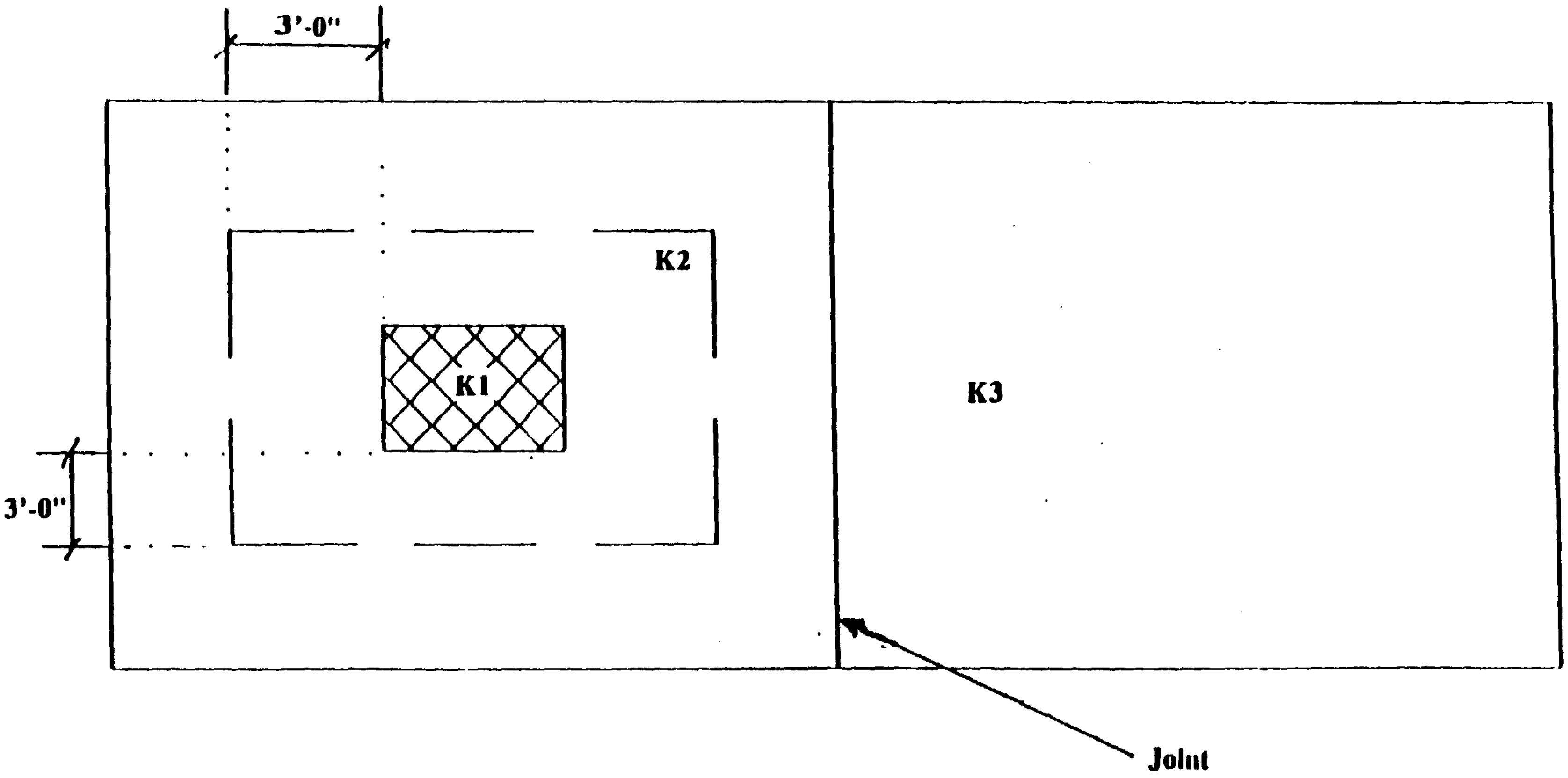


FIG. 3.13. Variation of k in the Different Regions for FE Idealization

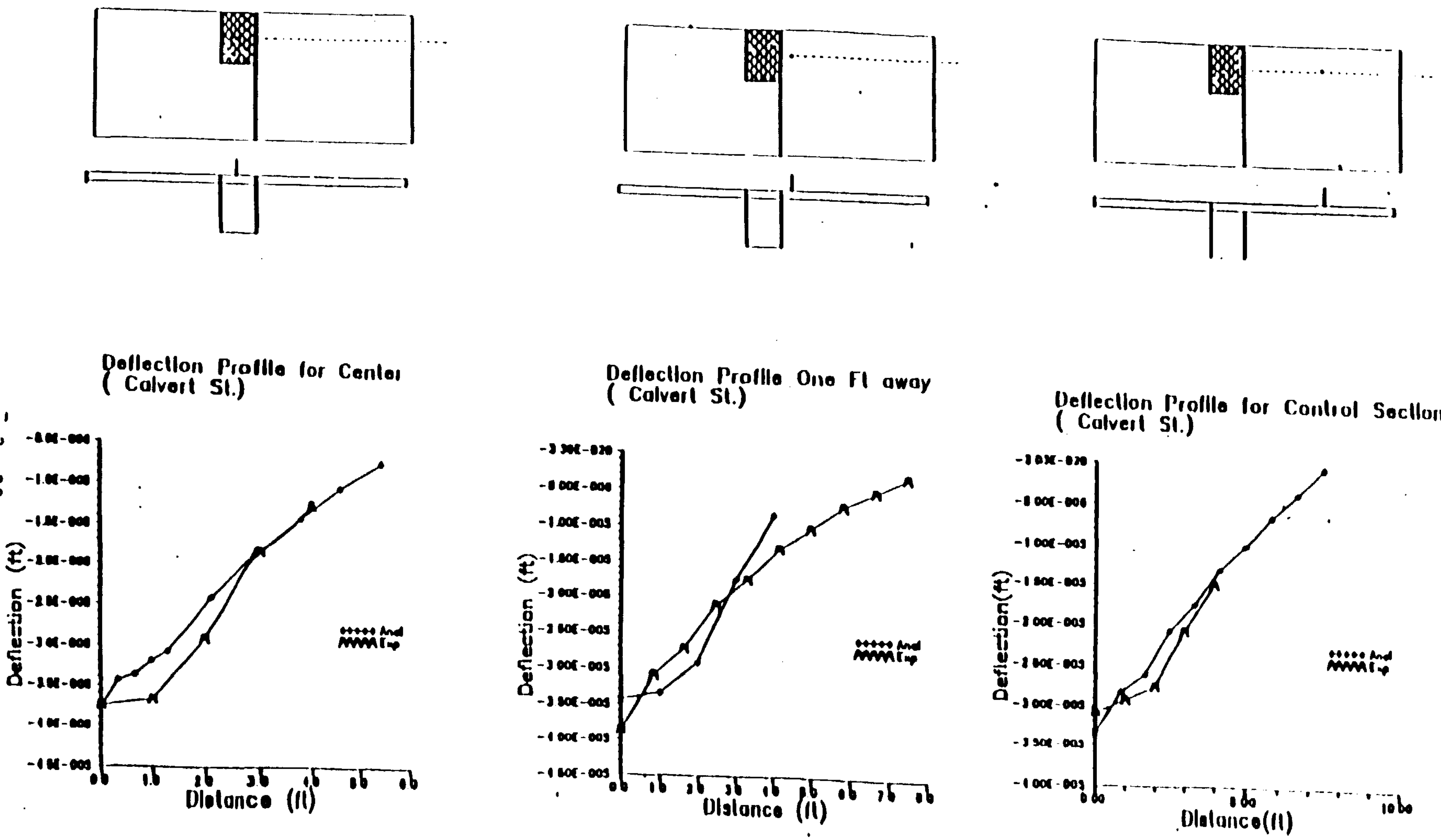


FIG. 3.14. Deflection Profiles of Measured and Analytical Response for Calvert St.

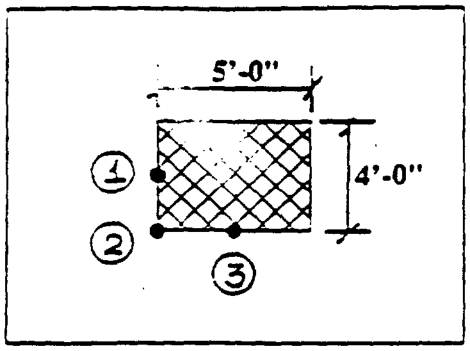


FIG. 3.15. Location and Loading of Center Cut

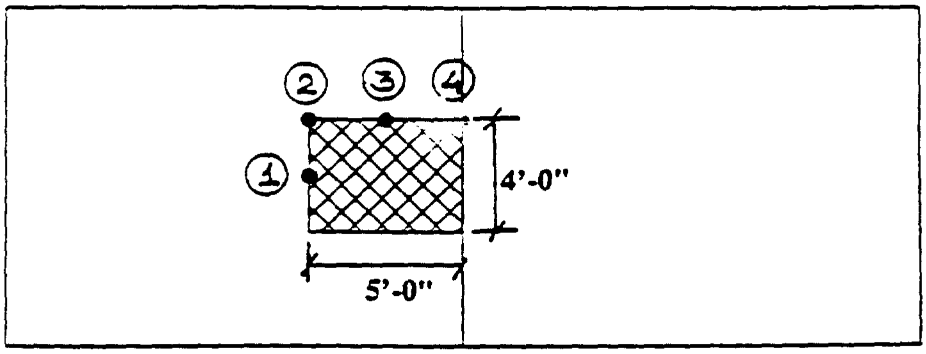


FIG. 3.16. Location and Loading of Edge Cut at Interior Joint

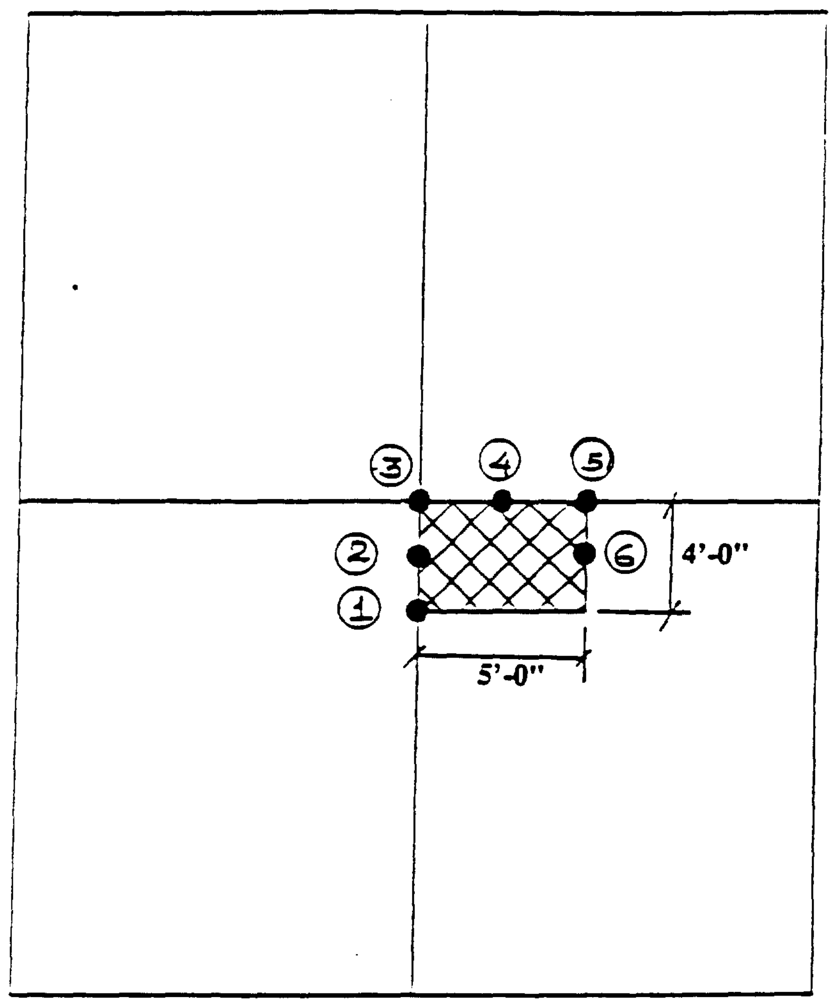


FIG. 3.17. Location and Loading of Interior Corner Cut

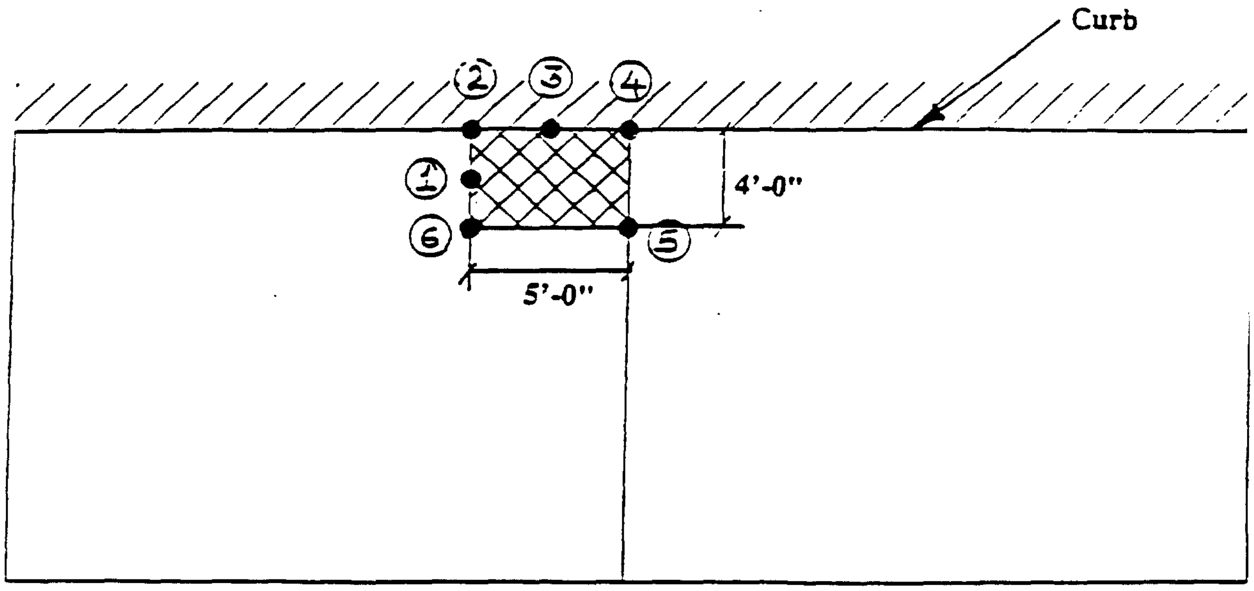


FIG. 3.18. Location and Loading of Cut at Curb

Load Conditi ... (5x4 Cut in the Center)

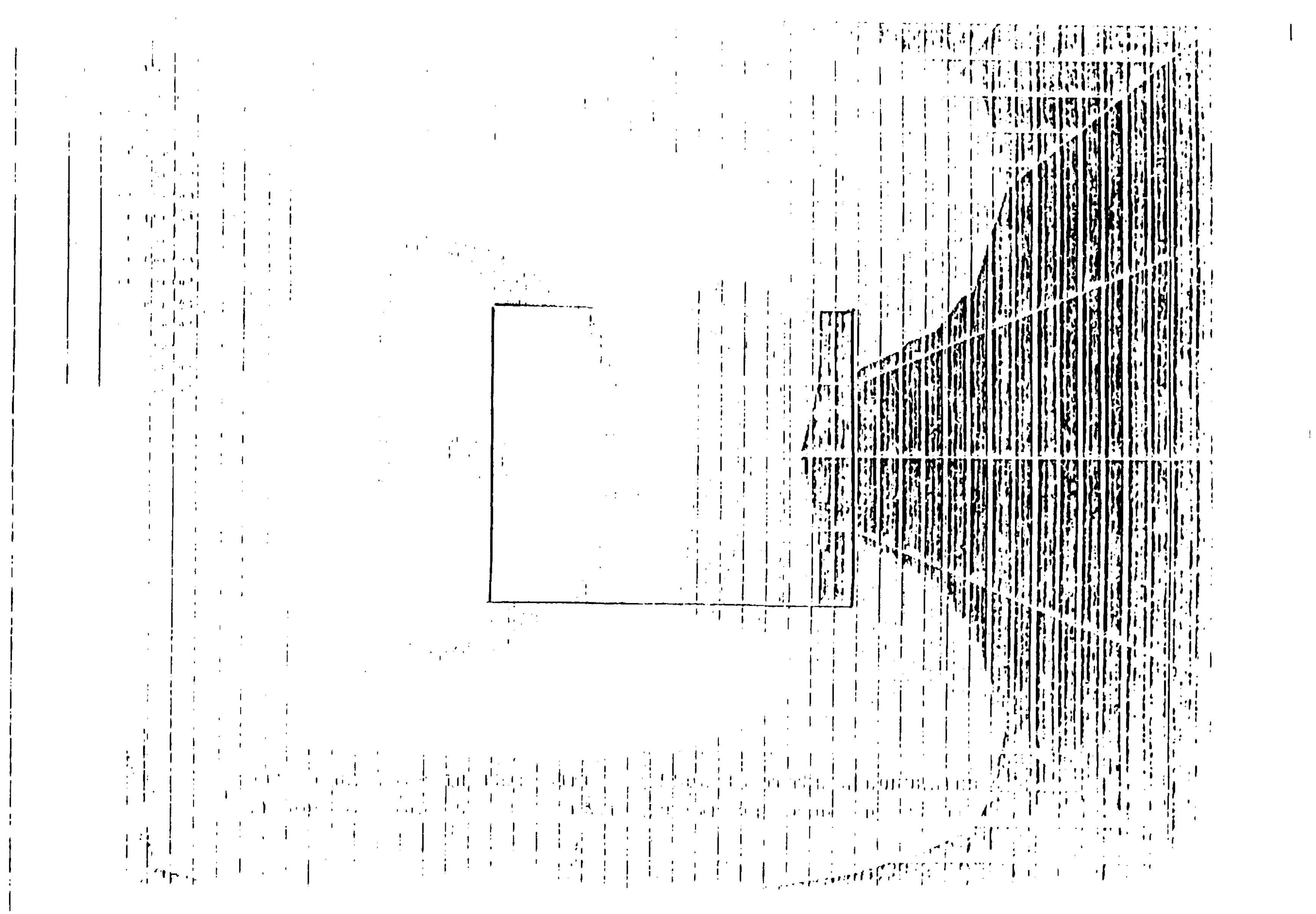


FIG 3.19.a. von Mises Stresses for Center Cut (Load Location # 1)

Load Condition . ,4 Cut in the Center)

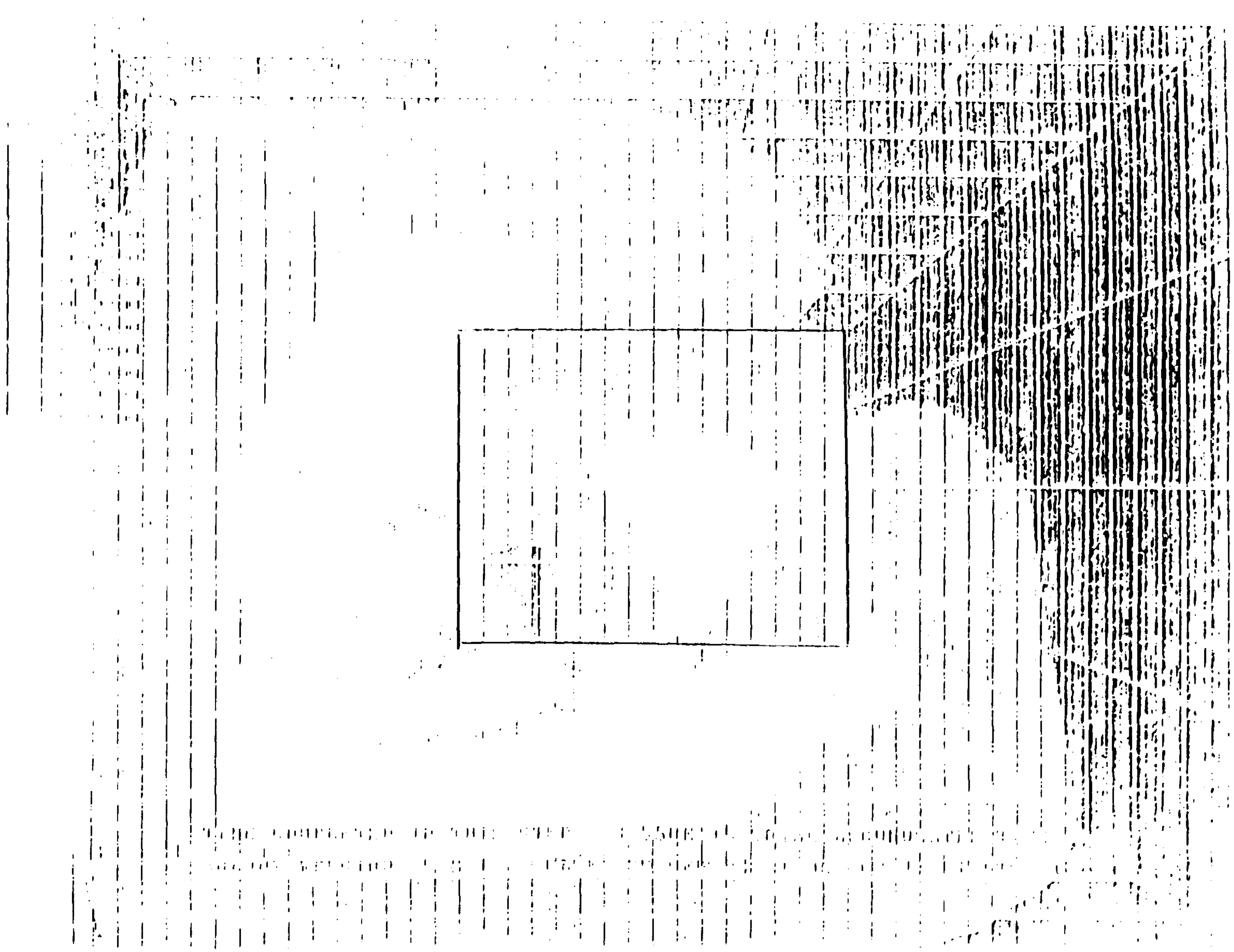


FIG 3.19.b. von Mises Stresses for Center Cut (Load Condition # 2)